TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 124

DOWNWASH OF AIRPLANE WINGS.

By Max Munk and Gunther Cario.

From Technische Berichte, Vol. III, Part I.

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Introduction.

The data for the calculation of the air forces acting on the elevators, obtained from previous model experiments are not immediately applicable in practice, as the angle at which the control surfaces meet the air stream is, in general, still unknown. The air stream, when it reaches the elevator has already been deflected by the wings and although the velocity imparted to the air current by the wings is of negligible amount compared with the speed of flight, the air behind the wings has been deflected downwards, so that the elevators work in an air-stream which is inclined in a downward direction. The angle at which the air stream meets the elevator surface is, therefore, different from, and, with the usual arrangement of elevators, less than the angle made by the elevator surfaces with the line of flight.

Test Installation. - In order to determine the value of the angle ϵ, that is, the difference between the aerodynamic, or effective angle of attack, and the geometrical, actual angle between the elevator control surfaces (stabilizer and elevators) and the direction of flight the Göttingen Institute carried out several series of tests, the results of the first set being now

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available. The object of these tests was to determine, under different conditions of flight, the direction of the air stream in the wake of the wings, which direction varies, in general, at different points. The test installation shown in Fig. 1 was designed for this purpose.

The airfoil used had a span of 720 mm (28.35 in) and a chord of 120 mm (4.725 in), and was tested in the large wind tunnel. It was suspended from the balance, by thin wires, in such a manner as to permit of the easy variation in the angle of attack when desired. The values of the lift and pressure head of the air current were recorded for each of the measuring points. Two rows of vertical wires were also arranged 108 mm (4.25 in) and 391 mm (15.39 in) respectively, from the trailing edge of the airfoil and parallel to the leading edge. To these wires thin silk threads about 200 mm (7.86 in) long were attached, at three different heights, namely, on a level with the leading edge and at 100 mm (3.93 in) above and below it, with the object of indicating the direction of the air stream. The air current was directed on the airfoil horizontally (see Table I).

Table I - Sequence of the six rows of threads.

Distance from leading edge	Percent of span	Distance of the respective rows, in percent of span, behind the leading edge.	
		0.317 b	0.71 b
Above L.E.	+0.139 b	No. 1	No. 2
Level	0.00	No. 3	No. 4
Below L.E.	-0.139 b	No. 5	No. 6

There are thus projected on the plane of symmetry of the airfoil, six rows of threads, whose points of attachment lie on parallels to the leading edge. It is necessary to distinguish between the rows of threads at the level of the wing, those above, and those below it. The threads nearest the airfoil are known as the front row, the others form the rear row.

At each test, as soon as the airstream had settled down, a photograph of the threads was taken from the side, on a plate placed parallel to the plane of symmetry of the airfoil. The threads were parti-colored black and white with different markings for each row and thus appear on the plate as variously broken lines, rendering identification easy and certain. The exposure was 2 - 3 seconds. A second photograph was simultaneously taken from above, on a horizontal plate, in order to ascertain whether the threads took up a sufficiently accurate position in their vertical planes and parallel to the direction of the air stream, and whether the angles read from the first plate could be taken as truly indicating the actual downward deflection. In all the tests this was found to be the case throughout. A photograph was also taken of the threads in the wind tunnel with the airfoil removed, in order to obtain the direction corresponding to and representing the direction of flight. A wire at right angles to the air stream served as a base line, from which all angles were measured on the photograph by means of a micrometer.

The Tests. - The tests described were carried out on a series of rectangular single wings, with an aspect ratio of 6. There was no fuselage. Two airfoils were without warp along the span and differed only in the shape of the section. The remaining six models had varying degrees of warp along the airfoil, the angle of attack increasing or decreasing uniformly from the center outwards, τ denoting the angle of attack at the extreme ends of the airfoil when that of the central section is 0°.

The experiments were carried out as described above without any difficulty being encountered. It was observed, however, that the threads in the space to the rear of the wing tips exhibited a tendency to describe a sort of elongated cone, instead of settling steadily in the direction of the airstream. Readings could not, therefore, be obtained from these threads.

Representation of the Results of the Tests.

The values of the lift coefficient and the angles of attack are given in Table II, for the entire series of tests. Figs. 2 to 9 give a rough diagrammatic sketch of the deflections of the air flow as recorded, which give a sufficiently accurate idea of the path of the air current. Each figure represents data for one airfoil. The distances of the points on the diagrams from the central vertical line correspond to the distance of the corresponding thread from the plane of symmetry of the airfoil. The points to the left of the center line refer to the front row of threads and those to the right of the line, to the rear row. Thus, only one-half of each curve is represented on the diagrams, with the object of giving a more complete illustration. This is the usual practice when representing a symmetrical body, one half, up to the axis, being shown in elevation, the other half in section. The curves join all the points corresponding to one angle of attack. The groups of curves, one above another, represent the rows of threads at various height. The downward deflection (downwash) given by the wing to the air current is indicated by the angle ϵ in degrees, above and below; the downward inclination correspo to a downward deflection of the air stream, and the consequent reduction in the angle of attack of the elevator at this point. It should, however, be noted, that only the points represented by small circles represent values obtained from actual observation, and hence, the paths of the curves passing through them are somewhat arbitrary and must not be taken as rigid. This is especially true of the region immediately behind the wing tips where, for reasons given above, no reliable data concerning the angle of downwash could be obtained. It is, therefore, possible that at these points the curves follow quite a different direction from that shown. As, however, this is the least likely place for fitting the elevator gear, the shape of the curves for positions immediately behind the wing tips is not of material importance here.

Table II - Angle of attack and lift coefficient.

b = 720 mm, t = 120 mm, $F/b^2 = 1 : 6$, $q = 25\ kg/m^2$.

Section No.	120		210		134			
Model No.	914		915		916		917	
Figure No.	2		3		4		5	
Angle of washin and washout τ	0		0		washin 4.5°		washin 3°	
	α	C_L	α	C_L	α	C_L	α	C_L
Angle of attack α and Lift coefficient. C_L	-4.0°	27	-5.2°	-21	-3.4°	-14	-3.8°	6
	-0.9	54	-1.7	17	-1.0	34	-1.0	33
	0	61	0.3	40	2.0	57	2.3	58
	4.5	96	3.0	62	4.9	78	5.3	79
	7.5	118	5.6	80	8.0	101	7.7	89
	10.5	138	7.0	97				

Table II (Contd.)

Section No.	134							
Model No.	918		919		920		921	
Figure No.	6		7		8		9	
Angle of washin and washout τ	washin 1.5°		washout -1.5°		washout -3°		washout -4.5°	
	α	C_L	α	C_L	α	C_L	α	C_L
Angle of attack α and Lift coefficient. C_L	-2.6°	10	-2.9°	-2	-3.0°	-8	-2.7°	-14
	-0.7	29	-2.0	8	-0.5	20	-0.4	-13
	1.8	48	0.3	29	1.9	39	2.4	36
	5.2	73	3.1	50	5.2	64	5.5	58
	7.2	87	5.8	72	7.4	86	7.1	78

Results of Measurements. - The conditions existing in the region behind the wing can be readily seen from an examination of Figs. 2 to 9. The saddle shape of the curves at the wing level should be specially noted. This formation was also found to exist with most of the warped wings in which the angle of attack decreased towards the wing tips. These wings also, produced a smaller downward deflection of the air stream at the center than towards the tips.

A comparison between the results of tests on the two wings with uniform section throughout, without warp, in Figs. 2 and 3, shows that the deflection of the air stream is approximately proportional to the lift coefficient. If we then confine ourselves to warped wings in which the angle reaches $\pm 3^{\circ}$ and examine the corresponding curves obtained, the difference between them can be readily seen. Special attention should be paid to the form of the curves relating to the central portion of the wings; and this is the part which is of the greatest importance having regard to the usual position of the elevator. Over this portion for a given lift coefficient, it will be seen that the angle of downwash is approximately uniform for all degrees of warping. The experiments, therefore, demonstrate that the existence of a twist in a wing has no great influence upon the angle of attack of the elevator when fitted to the rear of the central portion of the wing.

Theory, and Review of Results. - There is both a general and a special theory of airfoils. The special theory assumes, in advance, that the lift is distributed over the full span of the wing, the pressure at any point being proportional to the ordinates of a semi-ellipse having a major axis equal to the span. Calculation shows that the downward current behind such a wing is uniform along the whole span. The experiments just described, however, show that this is not generally the case and that the assumption was, therefore, inaccurate. It is noteworthy, however, that conclusions based upon this assumption often correspond very well with the observed results.

The general theory leaves the question of the distribution of the lift along the span open for the present, and assumes that it is uniform at all angles of attack; but no conclusions as to the angle of downwash ϵ of the various points of the wing can, as yet, be drawn. It is, however, clear, that this angle is the product of a constant "g" and the induced angle of attack (see E, Munk, "Some observations on the aerodynamics of supporting planes" T.B. Vol.II, No.2, p.187), viz:-

$$\epsilon = g \frac{C_L F}{b^2 \pi} 57.3^\circ \qquad \text{for monoplanes} \quad (1)$$

$$\epsilon = g \frac{C_L F}{k^2 b^2 \pi} 57.3^\circ \qquad \text{for multiplanes} \quad (2)$$

The values of "g" must first be established by experiment. It varies not only with the arrangement of the wings, but also from point to point on the wing.

If equation (1) is used for points behind the central portion of the wing, substituting the average values obtained by measurement at the three middle points of each row.

$$g = \frac{1}{57.3} \frac{\epsilon}{C_L \ F/b^2 \pi}$$

and, although not entirely constant for all points, it varies within such narrow limits as allow of an average value for all points to be taken. Table III, tabulating these averages, indicates in fact, that they do not vary greatly for different airfoils, and that the angle of downwash does not vary greatly from the direction of flight. This greatly facilitated the making of the experiments, as otherwise, the threads would have been curved instead of straight, making the reading of the angles of deflection extremely difficult. Taking the mean value from the bottom row of Table III, the results of the entire series of tests can be summarized as follows: The angle of attack at the tail unit, when in its usual position, is diminished by an amount equal to 1.8 times the induced angle of attack of the wings.

Table III - Values of the deflection coefficient g for mean points on the indicating threads.

Model No.	Section No.	Angle of warp	Fig. No.	Numerical designation of row. 1	2	3	4	5	6
914	190	0	2	1.3	1.2	1.7	1.6	1.4	1.6
915	210	0	3	1.4	1.3	1.9	1.9	1.5	1.5
916	134	4.5 *	4	1.3	1.2	1.7	1.7	1.5	1.5
917	134	3.0 *	5	1.5	1.3	1.7	1.8	1.6	1.7
918	134	1.5 *	6	1.6	1.3	1.7	1.7	1.6	1.4
919	134	-1.5 **	7	1.6	1.3	1.9	1.8	1.6	1.7
920	134	-3.0 **	8	1.5	1.4	2.0	1.7	1.4	1.5
921	134	-4.5 **	9	1.5	1.2	2.2	1.7	1.5	1.4
Mean				146	127	195	174	151	154

* Angle of washin.
** Angle of washout.

Translated by the National Advisory Committee for Aeronautics.

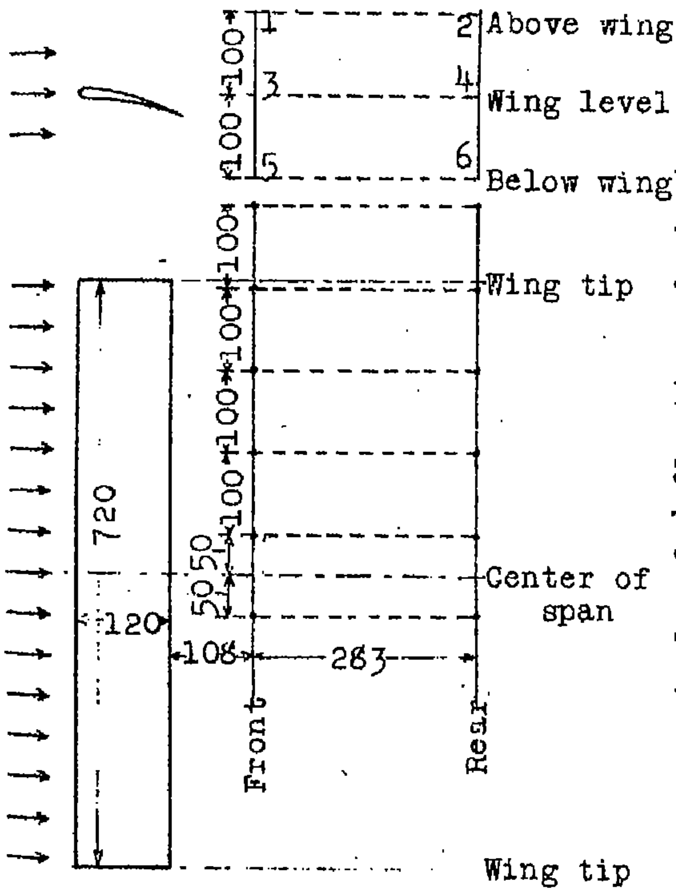


Fig.1 Arrangment for tests.

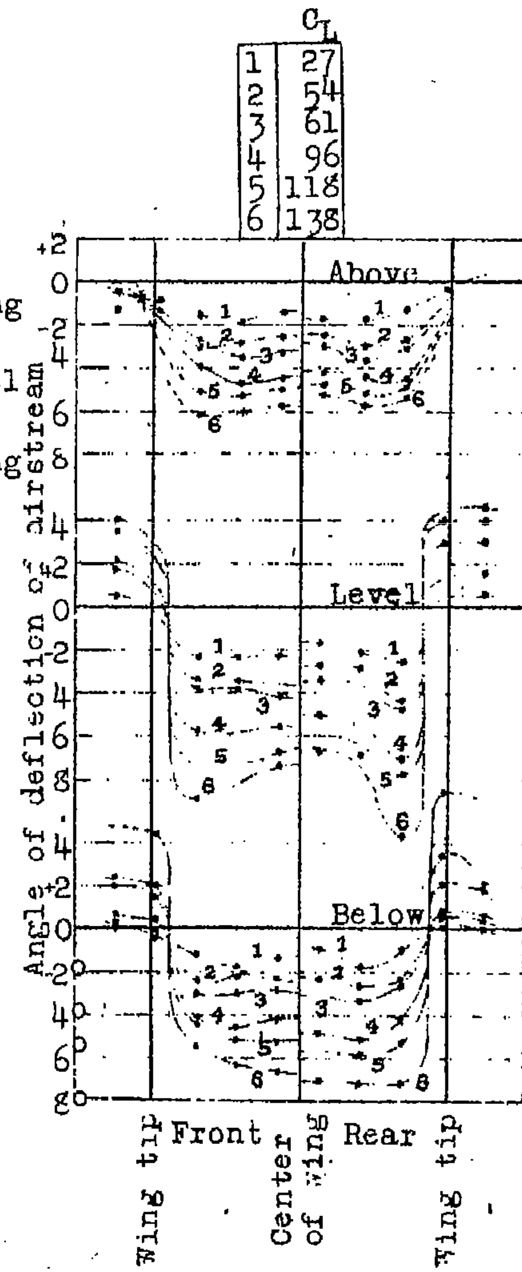


Fig.2 Angle of warping 0.0°

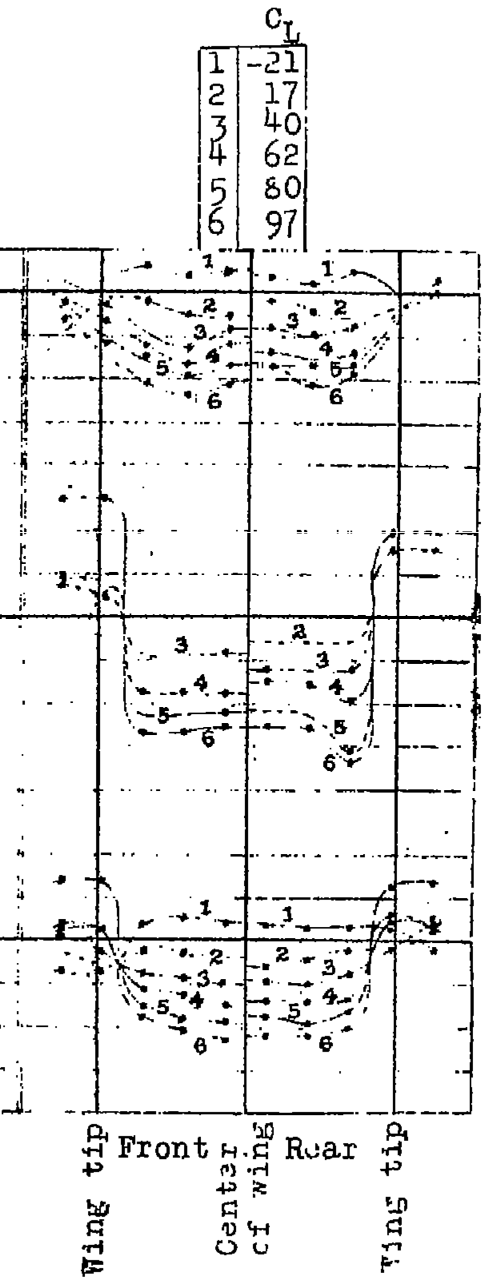
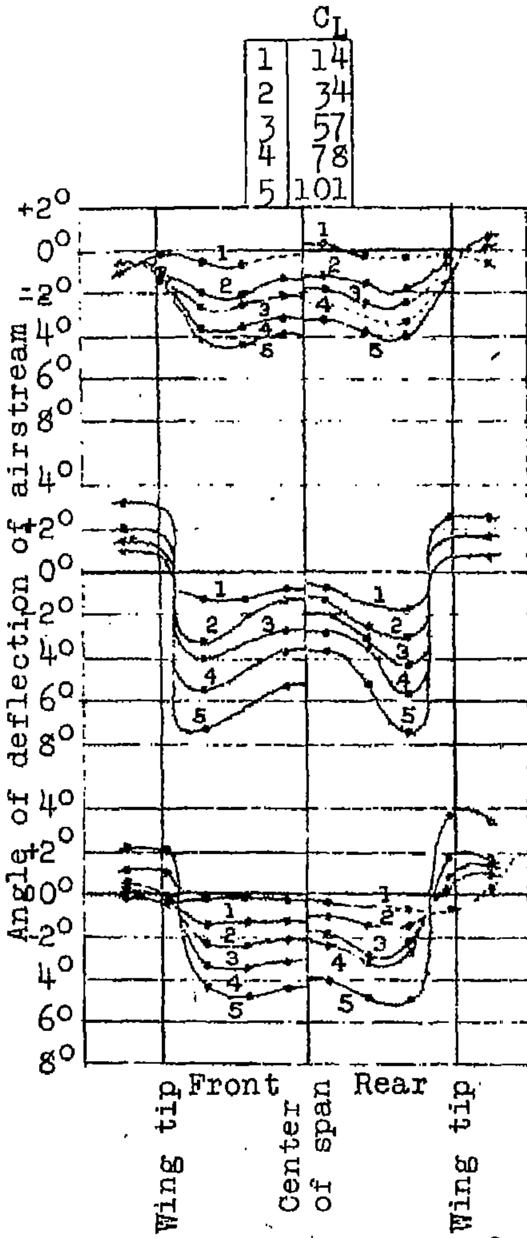
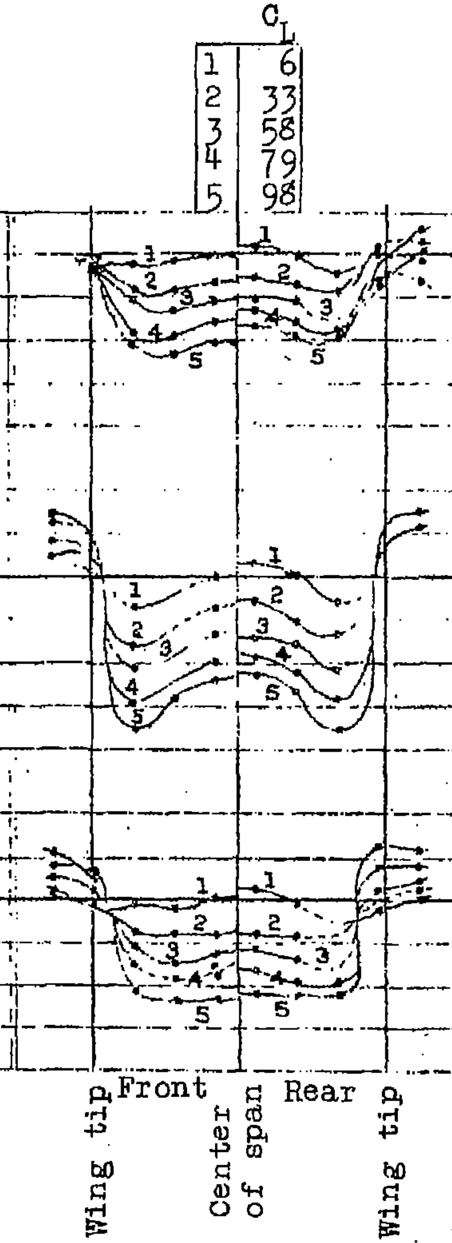


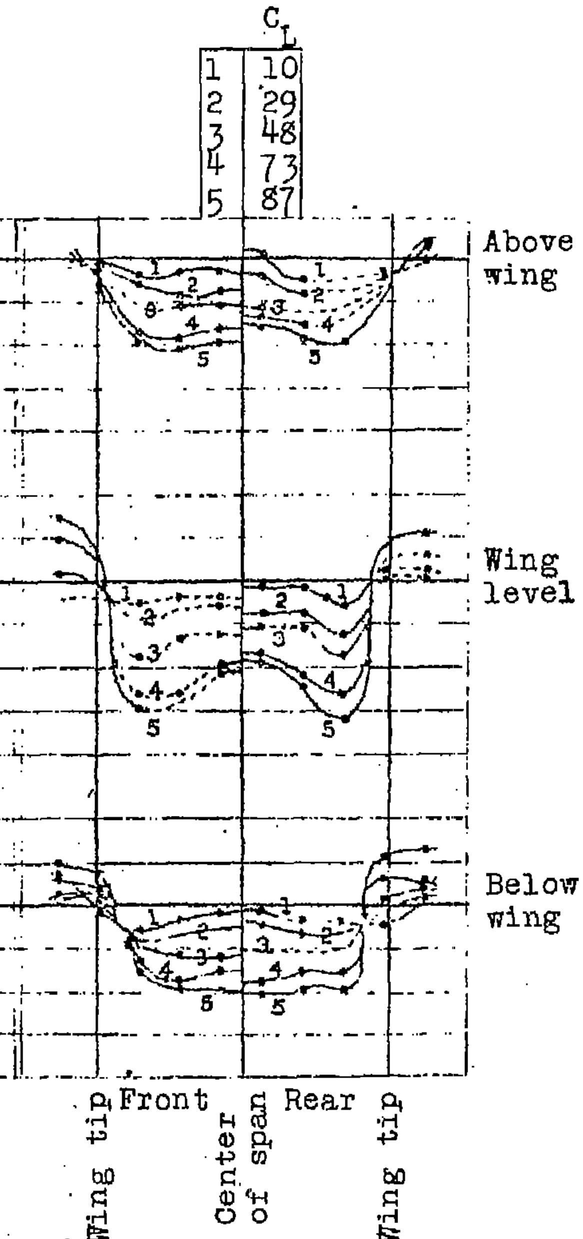
Fig.3 Angle of warping 0.0°



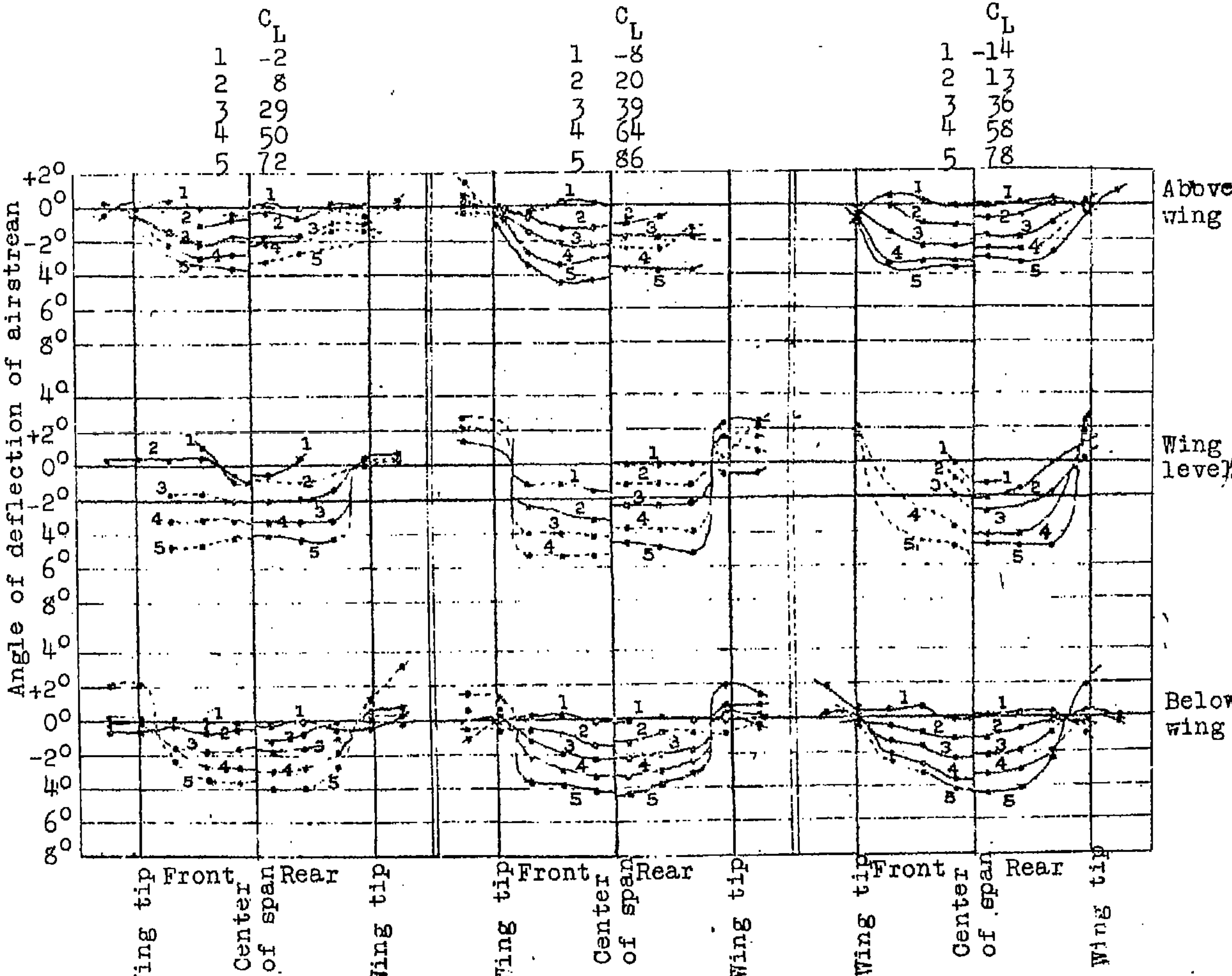
Angle of washin 4.5°
Fig. 4



Angle of washin 3.0°
Fig. 5



Angle of washin 1.5°
Fig. 6



Angle of washout -1.5°
Fig.7

Angle of washout -3.0°
Fig.8

Angle of washout -4.5°
Fig.9